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Subarctic Front migration at the Reykjanes Ridge during the mid- to late Holocene: evidence from planktic foraminifera

KERSTIN PERNER, MATTHIAS MOROS, EYSTEIN JANSEN, ANTOON KUIJPERS, SIMON R. TROELSTRA AND MAARTIN A. PRINS

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Expansion of fresh and sea-ice loaded surface waters from the Arctic Ocean into the sub-polar North Atlantic is suggested to modulate the northward heat transport within the North Atlantic Current (NAC). The Reykjanes Ridge south of Iceland is a suitable area to reconstruct changes in the mid- to late Holocene fresh and sea-ice loaded surface water expansion, which is marked by the Subarctic Front (SAF). Here, shifts in the location of the SAF result from the interaction of freshwater expansion and inflow of warmer and saline (NAC) waters to the Ridge. Using planktic foraminiferal assemblage and concentration data from a marine sediment core on the eastern Reykjanes Ridge elucidates SAF location changes and thus, changes in the water-mass composition (upper ~200 m) during the last *c.* 5.8 ka BP. Our foraminifer data highlight a late Holocene shift (at *c.* 3.0 ka BP) in water-mass composition at the Reykjanes Ridge, which reflects the occurrence of cooler and fresher surface waters when compared to the mid-Holocene. We document two phases of SAF presence at the study site: from (i) *c.* 5.5 to 5.0 ka BP and (ii) *c.* 2.7 to 1.5 ka BP. Both phases are characterized by marked increases in the planktic foraminiferal concentration, which coincides with freshwater expansions and warm subsurface water conditions within the sub-polar North Atlantic. We link the SAF changes, from *c.* 2.7 to 1.5 ka BP, to a strengthening of the East Greenland Current and a warming in the NAC, as identified by various studies underlying these two currents. From *c.* 1.5 ka BP onwards, we record a prominent subsurface cooling and continued occurrence of fresh and sea-ice loaded surface waters at the study site. This implies that the SAF migrated to the southeast of our core site during the last millennium.

Kerstin Perner (kerstin.perner@io-warnemuende.de) and Matthias Moros, Department of Marine Geology, Leibniz Institute for Baltic Sea Research, See Str. 15,18109 Rostock, Germany; Kerstin Perner and Eystein Jansen, Department of Earth Science and Bjerknes Centre for Climate Research, University of Bergen, Allégaten 41, Bergen 5055, Norway; Antoon Kuijpers, Geological Survey of Denmark and Greenland, Øster Voldgade 10, Copenhagen DK-1350, Denmark; Simon R. Troelstra and Maartin A. Prins, Faculty of Earth and Life Sciences, Vrije Universiteit, de Boelelaan 1085, Amsterdam 1081HV, The Netherlands; *received 26th August 2016, accepted 11th April 2017.*

The mid- to late Holocene (last *c.* 6000 years) North Atlantic region experienced distinct climatic and oceanic changes, which have been attributed to various external and internal forcing mechanisms, including solar variability, freshwater fluxes and variations in the strength of ocean circulation (e.g. Bond *et al.* 2001; Andersen *et al.* 2004a; Kaufman *et al.* 2004; Mayewski *et al.* 2004; Hald *et al.* 2007; Jansen *et al.* 2008; Wanner *et al.* 2008; Andersson *et al.* 2010). Changes in the northward heat flow by the North Atlantic Current (NAC) and its extensions (Fig. 1) play an important role, as this current draws warm and saline waters from the subtropics and forms the surface limb of the Atlantic Meridional Overturning Circulation (AMOC). The dynamics of the Subpolar Gyre influence the NAC's properties (Fig. 1). During times of a strong and contracted (weak and expanded) circulation, the gyre contributes more (less) warm and saline waters to the NAC (e.g. Hansen & Østerhus 2000; Häkkinen & Rhines 2004; Hátún *et al.* 2005; Born *et al.* 2013). Observational studies show that freshwater advection around the gyre, originating in the East Greenland Current (EGC) and the Labrador Current (LC), influence gyre dynamics (Fig. 1A; e.g. Hátún *et al.* 2005; Häkkinen *et al.* 2011). A prominent example of this influence are the mid- to late 20th Century Great Salinity Anomalies (GSAs; Dooley *et al.* 1984; Dickson *et al.* 1988; Belkin *et al.* 1998; Otterå & Drange 2004; Bersch *et al.* 2007; Sundby & Drinkwater 2007; Thornalley *et al.* 2009). Furthermore, Bersch *et al.* (2007) documented that increased freshwater advection from the Arctic Ocean accompanies enhanced contribution of subtropical waters into the sub-polar North Atlantic. However, there is still limited knowledge on the freshwater expansion beyond the instrumental data period and its influence on millennial-scale regional changes of oceanic conditions during the mid- to late Holocene.

A suitable location to investigate the spatial extent of fresh waters from the EGC route, which circulate around the gyre, is the Reykjanes Ridge area, south of Iceland. Here, the location of the Subarctic Front (SAF) separates warm and saline surface waters (NAC-fed) of the Iceland Basin from the cooler and fresher waters of the Irminger Basin (EGC-fed; Fig. 1B, C). Observational studies reveal that the location of the front is determined by the EGC's freshwater input and marks the maximum southward extent of sea-ice drift in the central North Atlantic Ocean. A large contrast between water-mass properties of the Iceland (warm/saline) and Irminger Sea (cold/fresh) leads to the development of a distinct SAF at

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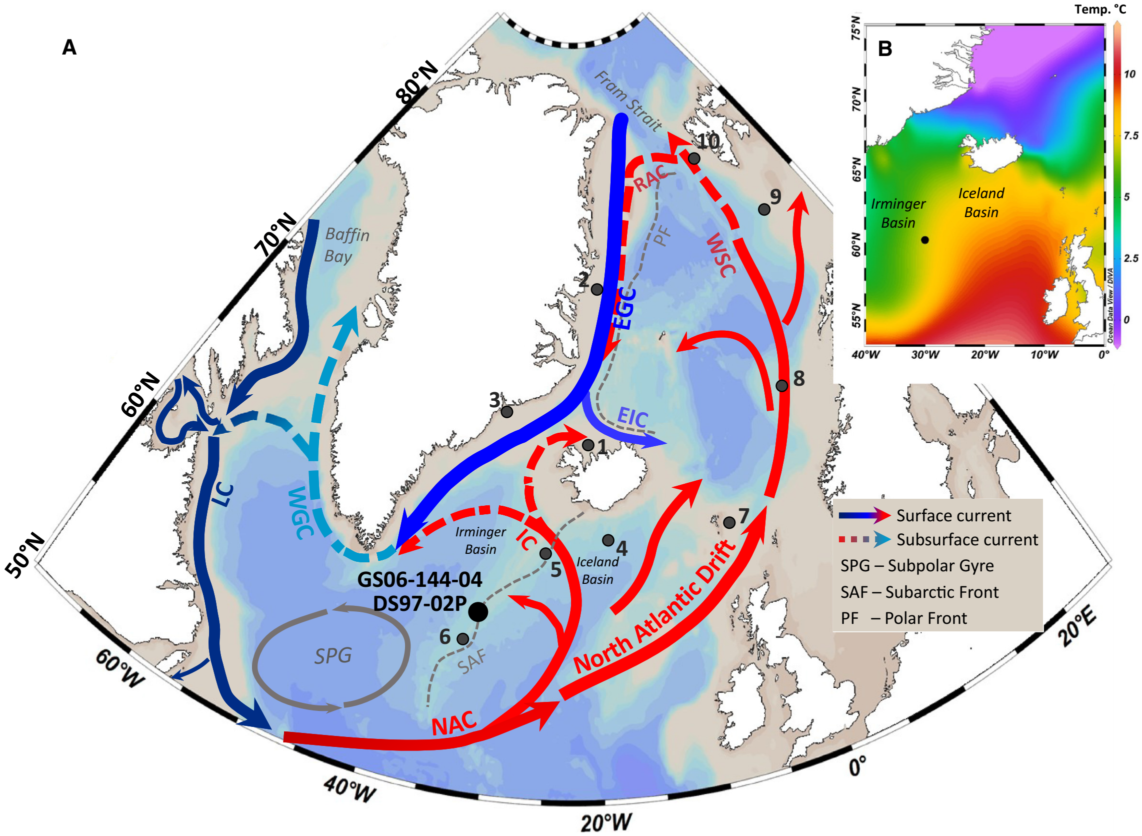


Fig. 1. A. Schematic map of ocean circulation in the North Atlantic region and location of the cores GS06-144-04 (short multi core) and DS97-02P (long piston core) at the eastern flank of the Reykjanes Ridge. EGC = East Greenland Current; EIC = East Icelandic Current; WGC = West Greenland Current; LC = Labrador Current; IC = Irminger Current; NAC = North Atlantic Current; NwAC = Norwegian Atlantic Current; WSC = West Spitzbergen Current. Numbers 1–10 indicate locations of core sites discussed within the text: 1 = Moros *et al.* (2006a)/Cabedo-Sanz *et al.* (2016); 2 = Perner *et al.* (2015); 3 = Andrews *et al.* 1997; 4 = Thornalley *et al.* (2009); 5 = Hall *et al.* (2004); 6 = Balestra *et al.* (2010)/ Solignac *et al.* (2009); 7 = Rasmussen & Thomsen (2010); 8 = Risebrobakken *et al.* (2003); 9 = Sarnthein *et al.* (2003); 10 = Müller *et al.* (2012)/ Werner *et al.* (2013). B. Winter (January to March) sea surface temperature obtained from the World Ocean Data Atlas (WOA13) for the study area (www.odv.de). The black dot marks our core location at the Reykjanes Ridge. [Colour figure can be viewed at www.boreas.dk]

the Reykjanes Ridge (Belkin & Levitus 1996; Bersch *et al.* 2007). In order to identify mid- to late Holocene changes in the location and characteristics of the SAF, assemblage studies of planktic foraminifer provide a suitable tool, as certain species show a close affinity to specific water-masses and environmental conditions (Phleger 1960; Bé 1977; Hemleben *et al.* 1989; Murray 1991). Changes in species abundances allow the identification of variations in the influence of water-masses from Iceland vs. Irminger Sea that link to SAF migration at the Ridge, which are expressed as changes in relative temperature and water column stratification. Furthermore, the calculation of species concentration (number g^{-1} sediment) provides additional information on productivity changes in surface (upper 200 m) and subsurface waters that link to the influence of oceanic fronts, i.e. development of a marked SAF at the Reykjanes Ridge.

Here, we present a new planktic foraminifer record from the eastern flank of the Reykjanes Ridge, near the present-day location of the SAF that spans the mid- to late Holocene (Fig. 1, cores GS06-144-04-MC and DS97-02P). This record complements published data from core DS97-02P (Moros *et al.* 2012) including stable oxygen ($\delta^{18}O$) records based on three planktic foraminifer species, *Globigerina bulloides*, *Neogloboquadrina incompta* and *Globorotalia inflata*, which covers the time from *c.* 5.8 to 0.7 ka BP. We extend this record towards the present, by providing $\delta^{18}O$ measurements on these three species from core GS06-144-04-MC. The combined foraminifer and stable isotope records allow a more in-depth view of oceanic conditions at the eastern Reykjanes Ridge. We compare our data with selected sites along the Arctic Ocean freshwater route, i.e. EGC, to improve our knowledge on the regional impact of freshwater expansion during the last *c.* 6000 years.

Oceanographic setting

The study area (latitude 58°N, longitude 30°W) is located on the eastern flank of the Reykjanes Ridge, an oceanographically dynamic area south of Iceland near the SAF (Fig. 1). South of Iceland, the northeast–southwest trending SAF is well developed at ~53°N and separates the colder Irminger Sea from the warmer Atlantic waters in the Iceland Sea. The upper 800 m above the eastern side of the Ridge consists of Subpolar Mode Water with temperature exceeding 6 to 7 °C and salinity of ~35.1 PSU (Gudfinnson *et al.* 2008). Between 53°N and 60°N, the IC, a westward deflection of the NAC, crosses the Reykjanes Ridge and separates southwest of Iceland into two branches. The major branch flows westwards and is incorporated into the EGC, forming the West Greenland Current (WGC), while the eastern branch forms the North Icelandic Irminger Current (NIIC) that continues northeastwards around Iceland (Fig. 1; Hurdle 1986; Krauss 1986). The EGC carries cold and fresh, ice-loaded waters from the Arctic Ocean via the Fram and Denmark Strait into the sub-polar North Atlantic Ocean (e.g. Malmberg 1985). These waters influence surface water conditions in the Irminger Basin and deep convection in the Labrador Sea (e.g. Hansen & Østerhus 2000; Häkkinen & Rhines 2004; Hátún *et al.* 2005). Average summer sea-surface temperature (SST) in the study area ranges from 9 to 12 °C, but may vary between 5 and 15 °C depending on the EGC transport regime (e.g. Levitus & Boyer 1994; Belkin & Levitus 1996; Yashayaev *et al.* 2007).

Ecological preferences of planktic foraminifers in the sub-polar North Atlantic

The opportunistic near-surface dwelling (upper 50 m) *Globigerina bulloides* (d'Orbigny, 1826) lives in the surface mixed layer and is most abundant during the spring to early summer blooms (Chapman *et al.* 2000; Ganssen & Kroon 2000; Schiebel & Hemleben 2000).

High abundances of the common sub-polar and near-surface (upper 100 m w.d.) dwelling species *Turborotalita quinqueloba* (Natland, 1938) and *Globogerinita uvula* (Ehrenberg, 1861) are often related to the presence of oceanic fronts and the resulting increased surface-water productivity (e.g. Bé & Tolderlund 1971; Hemleben *et al.* 1989; Kroon *et al.* 1991; Johannessen *et al.* 1994; Husum & Hald 2012).

Globogerinita uvula is an opportunistic species, associated with increased food supply connected to the influence of oceanic fronts (Boltovskoy *et al.* 1996; Bergami *et al.* 2009). Increased abundance of this species has been previously related to cooling of surface waters (Rasmussen & Thomsen 2010).

At greater water depth, i.e. just above the thermocline (~60–150 m), the mixed-layer and cosmopolitan species *Globogerinita glutinata* (Egger, 1893) and *Neogloboquadrina incompta* (Cifelli, 1961; (syn. *N. pachyderma* (Ehrenberg 1861), dextral)), are found (e.g. Tolderlund & Bé 1971; Fairbanks *et al.* 1980; Schiebel & Hemleben 2000; Kuroyanagi *et al.* 2006). *Neogloboquadrina incompta* favours warm and stratified surface waters. In the northeastern North Atlantic, this species calcifies at ~50 m and thus records near-surface water changes (e.g. Nyland *et al.* 2006; Andersson *et al.* 2010). Within the Polar Front area offshore north Iceland, *N. incompta* calcifies at slightly shallower water depths (30–40 m) throughout the year (Ostermann *et al.* 1998).

According to previous studies by Bé & Tolderlund (1971) and Johannessen *et al.* (1994), the sub-polar to polar species *Neogloboquadrina pachyderma* (sinistral, Darling *et al.* 2006 (syn. *N. pachyderma*; Ehrenberg, 1861)) occurs in relatively high abundances when summer temperatures remain below 9 °C. This species calcifies within the EGC in the upper 100 m of the water column (Kohfeld *et al.* 1996; Pados & Spielhagen 2014), while in areas with a deep permanent thermocline due to warm Atlantic Water influence this species thrives deeper within the mixed layer (50–200 m; Kohfeld *et al.* 1996).

South of Iceland, *Globorotalia inflata* (d'Orbigny, 1839) lives even deeper in the water column, at the base of the seasonal thermocline (~100–200 m; e.g. Ganssen & Kroon 2000; Cléroux *et al.* 2007). The occurrence of warmer waters from the NAC controls the abundance of this species (e.g. Tolderlund & Bé 1971; Ganssen & Kroon 2000; Pflaumann *et al.* 2003). According to plankton net studies from the eastern sub-polar North Atlantic within the Norwegian Atlantic Current (NwAC), the stable isotope composition of *G. inflata* records the physical properties (temperature/salinity) of the ambient water-masses, which are controlled by deep winter-time mixing (Ottens 1992b; Chapman 2010). Accordingly, depleted $\delta^{18}O$ values of this species reflect the occurrence of warmer and saltier waters at our study site.

The subtropical species *G. scitula* Brady, 1882, dwells near the surface and migrates during its life cycle into the mixed layer. The occurrence of this species within the sub-polar North Atlantic is clearly linked to the entrainment of warm and saline waters from the NAC (e.g. Hemleben *et al.* 1989).

Material and methods

A 36-cm-long multi core (GS06-144-04-MC; 58°54.73 N, 30°75.25W) was collected during the GS06-144 cruise with the RV 'G.O. Sars' in 2006, in 1683 m water depth (Dokken & Ninnemann 2006), near the previously sampled core site DS97-02P (Troelstra *et al.* 1997) on the eastern flank of the Reykjanes Ridge. Core DS97-02P, a 10.4-m-long piston core, was obtained in 1997 from 1685 m water depth during the Dutch Denmark Strait expedition on board the R/V 'Professor Logachev' (Troelstra *et al.* 1997).

For core DS97-02P, we use the age model previously published (Moros *et al.* 2012). The uppermost 1.50 m, which will be the focus of our study, covers the mid- to late Holocene (Prins *et al.* 2001, 2002; Rasmussen *et al.* 2002; Witak *et al.* 2005; Moros *et al.* 2012).

Table 1. AMS radiocarbon ages from the short multi core GS06-144-04, eastern flank of the Reykjanes Ridge, obtained from the planktic foraminifer *G. bulloides*. For the chronology of the long DS97-02P core, refer to Moros *et al.* (2012). BP = AD 1950.

Depth (cm)	Lab. code	^{14}C age (a BP)	Calibrated age (a BP, 1σ; ΔR = 0)
1	Poz-20540	103.74±0.52 pMC	n.a.
5.5	Poz-25790	102.53±0.41 pMC	n.a.
16	Poz-20541	675±30	277–360
18	ETH-5830	690±50	285–393
30.5	Poz-57334	900±40	481–538
30.5	Poz-25793	880±30	477–520
34.5	Poz-57335	950±30	508–565

Core GS06-144-04-MC extends the DS97-02P record towards the present. Age control of this core is based on six accelerator mass spectrometry (AMS) radiocarbon (^{14}C) dates obtained from planktic foraminifera (*G. bulloides*; Table 1) and radionuclide (^{137}Cs) measurements. In accordance with the age model from DS97-02P, all AMS ^{14}C dates from GS06-144-04-MC have been calibrated using the Marine09 calibration curve in Calib6.01 (Stuiver & Reimer 1993). A standard reservoir age of 400 years (ΔR = 0; Table 1) has been applied to the radiocarbon dates.

Measurements of the radiogenic isotope ^{137}Cs, performed on GS06-144-04-MC, allow identification of modern sediment deposition at the core site. Sediments used for ^{137}Cs analyses were freeze-dried and ball-milled. Measurements were carried out on a Germanium Detector (Canberra, BE3830-7500SL-RDC-6ULB). Atmospheric nuclear weapons tests, carried out in the late AD 1950s and early AD 1960s, caused a major release of ^{137}Cs into the atmosphere. In the Northern Hemisphere, a first wide ^{137}Cs distribution occurred in AD 1954 and a peak in atmospheric ^{137}Cs fall-out at AD 1963 (Pennington *et al.* 1973; Appleby *et al.* 1991).

A low-resolution record (10-cm sample interval) of planktic foraminiferal assemblage data was previously published by Rasmussen *et al.* (2002) from core DS97-02P, using the >106 μm fraction. Here, we present new planktic foraminiferal assemblage data performed on the dry residue of the >100 μm fraction, counted at 2 to 2.5 cm intervals (2-cm-thick slices). About 2 g of dry sediment was carefully sieved at 100 μm and subsequently dried at 45 °C. Planktic foraminifera were identified down to species level using a stereomicroscope following the taxonomy of Parker (1962) and Saito *et al.* (1981). All specimens were well preserved and no clear evidence of post-mortem dissolution changes were recognised. A minimum of 400 specimens was counted per sample.

Stable oxygen isotope measurements (δ^{18}O) were performed for core GS06-144-04-MC at 2-cm intervals on three planktic foraminiferal species (*Globigerina bulloides*, *Neogloboquadrina incompta* and *Globorotalia inflata*). These new data extend the DS97-02P stable isotope records from Moros *et al.* (2012) towards the present. All isotope analyses were carried out at the GMS laboratory of the Bjerknes Centre for Climate Research at the University of Bergen, using a Finnigan MAT 251 mass spectrometer equipped with an automatic 'Kiel device' preparation line. Prior to analyses, about six to 10 specimens of the fraction >150 μm were crushed and cleaned in an ultrasonic bath. The reproducibility of isotope measurements is ±0.07‰ based on replicate measurements of carbonate standards.

Results and interpretation

Age model of GS06-144-04-MC

The combined information from down-core radionuclide (^{137}Cs) measurements and AMS ^{14}C dating were used to develop an age model for core GS06-144-04 (Table 1, Fig. 2). Two AMS ^{14}C dates, obtained within the first 5 cm of the core, are considered as Bomb ^{14}C dates as the ^{14}C concentration exceeds 100 pMC (Table 1). This agrees well with the measured onset of ^{137}Cs deposition in the sediment at ~5 cm core depth, which we use as a time marker for the onset of atmospheric weapon testing at AD 1954 (Fig. 2, blue line). For age model development, we applied a linear fit between (i) AD 2006 – the year of core retrieval, (ii) the ^{137}Cs peak onset, and (iii) the calibrated AMS ^{14}C dates (Fig. 2, grey dashed line). Our age model shows that the sediments from GS06-144-04-MC cover the last *c.* 550 years. Accordingly, no overlap occurs

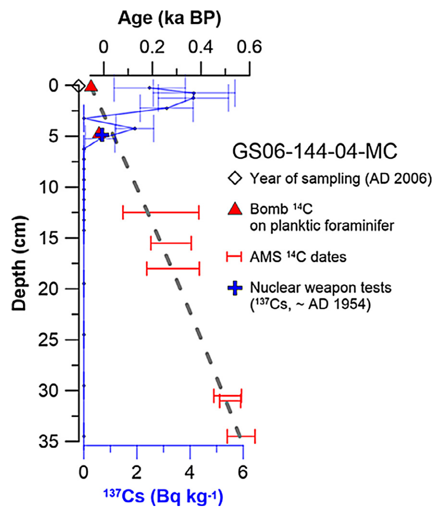


Fig. 2. Age vs. depth profile of the short multi core GS06-144-04 from the eastern Reykjanes Ridge, based on AMS ^{14}C dates (red) and ^{137}Cs measurements (light blue curve). The dashed grey line displays the developed age-depth model using a linear fit. [Colour figure can be viewed at www.boreas.dk]

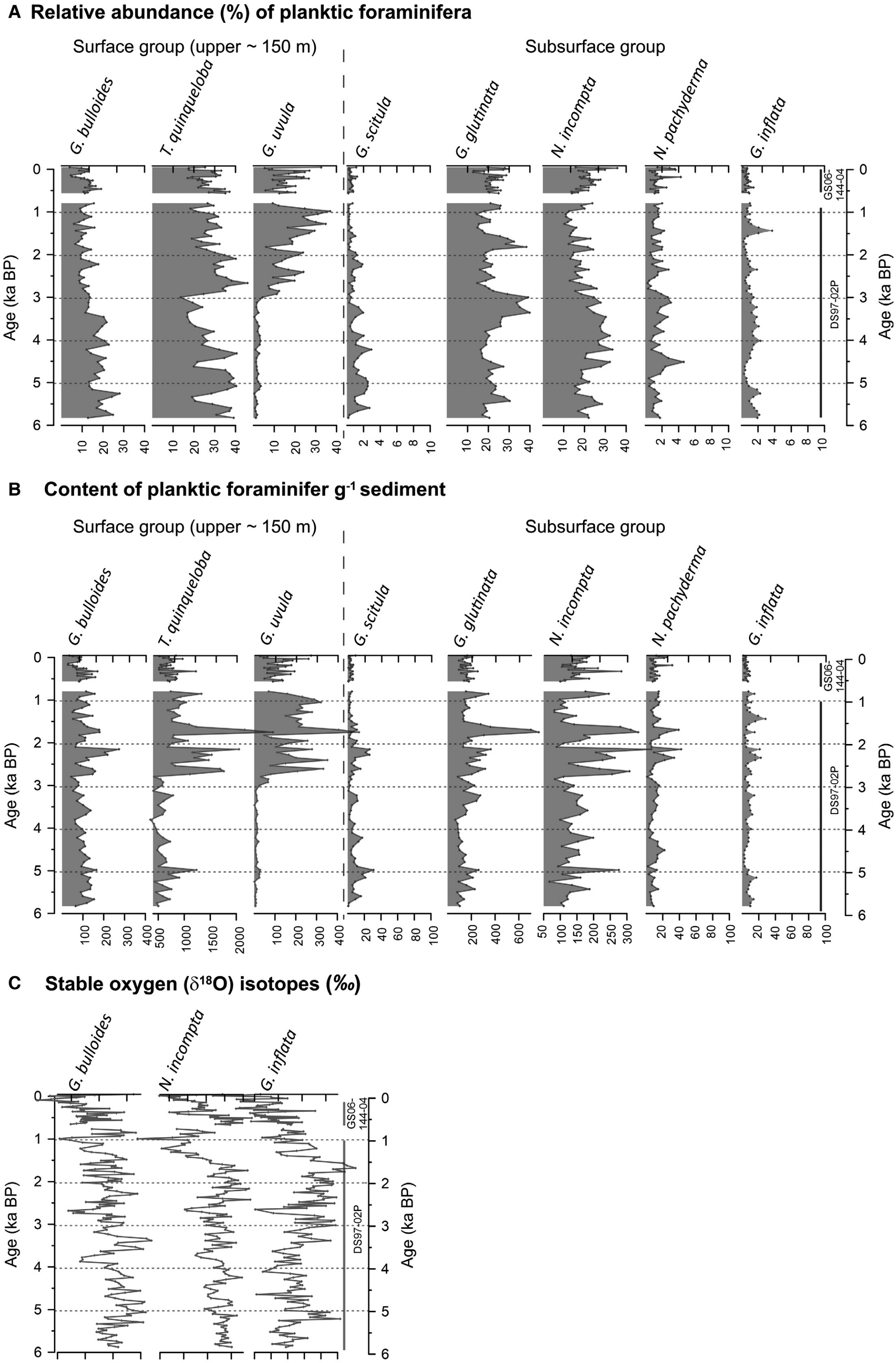


Fig. 3. Planktic foraminiferal assemblage (A) and occurrence per g sediment (B). C. $\delta^{18}O$ of surface-dweller *Globigerina bulloides*, mixed-layer species *Neogloboquadrina incompta* and thermocline dwelling *Globorotalia inflata* data of cores GS06-144-04 (this study) and DS97-02P (Moros *et al.* 2012) for the last *c.* 5.8 ka BP.

between GS06-144-04-MC and DS97-02P. Despite the gap of *c.* 100 years between the cores, plotting our proxy data on a combined age scale allows discussion of longer-term oceanic trends during the last millennium.

Changes in planktic foraminifer during the last c. 5.8 ka

In line with previous results from Rasmussen *et al.* (2002), we identified eight planktic foraminiferal species. The fauna is dominated by *T. quinqueloba*, *G. bulloides*, *N. incompta*, *G. glutinata* and *G. uvula*, which constitute ~80% of the total assemblage (Fig. 3). As accessory species, *G. scitula*, *G. inflata* and *N. pachyderma* are present. This diverse assemblage reflects a predominant influence of warm and saline waters originating from the NAC at our core site during the last *c.* 5.8 ka (Fig. 3A). In addition, we calculate the concentration of planktic foraminifer (number of specimens g^{-1} sediment), which provides information on changes in productivity at the site. We group our species into surface (EGC-influenced) and subsurface (NAC-influenced) productivity groups. Thereby, we consider the species preferences, i.e. habitat depths (see section: *Ecological preferences of planktic foraminifers*; Fig. 3B). The surface productivity group consists of *G. bulloides*, *T. quinqueloba* and *G. uvula*, while the subsurface group comprises *G. scitula*, *N. incompta*, *N. pachyderma*, *G. glutinata* and *G. inflata*.

The mid-Holocene (c. 5.8 to 3 ka BP). – This interval is characterized by overall high abundances of the oceanic front indicator *T. quinqueloba* (max. 40%), near-surface dweller *G. bulloides* (up to 25%), mixed-layer species *N. incompta* (max. 30%) and *G. glutinata* (average 20%). The faunal composition reflects a high productivity environment, predominantly influenced by warm/saline Atlantic waters at the surface and subsurface and a deep mixed layer and thermocline. The occurrence of *G. scitula*, although in low abundances (max. 3%), indicates the entrainment of subtropical waters into our study area (Fig. 3A). We find a ~20% abundance decrease of *T. quinqueloba* centred at *c.* 5.5 and 4.6 ka BP that probably relates to a reduced influence of the SAF owing to a northwestward or southeastward shift of the front. During both periods, we recognise a minor increase in *N. pachyderma* and a decrease in *G. scitula* (Fig. 3A). The planktic foraminifera flux reveals increased surface and subsurface water productivity in the time from *c.* 5.5 to 5.0 ka BP (Fig. 3B). This is indicative of a strengthening of the SAF during this period. From *c.* 4.5 to 3.0 ka BP, the abundance of *T. quinqueloba* decreases by 20%, paralleling the high abundance of *N. incompta* (up to 30%). Maximum abundance (up to 40%) of *G. glutinata* occurs in the time from *c.* 3.5 to 3.0 ka BP. An increase in subsurface productivity is found from *c.* 3.7 to 3.0 ka BP (Fig. 3B), which might be linked to the increase in subsurface water temperature during this period (Moros *et al.* 2012).

The late Holocene (last c. 3.0 ka). – During the interval from *c.* 3.0 to 1.0 ka BP, assemblage changes seem to be largely determined by the prominent increase in *G. uvula* abundance, which reaches ~30% at *c.* 1.0 ka BP (Fig. 3A). This accompanies a ~15% decrease in *T. quinqueloba* and *N. incompta*, a relatively low abundance (average 10%) of *G. bulloides* and a drop in *G. scitula* abundance to below 1% (Fig. 3A). The observed assemblage shift reflects a pronounced change in surface water composition, indicating a reduction of SST and occurrence of less warm/saline waters at the core site. We relate this assemblage feature to an enhanced influence of the SAF and thus of Irminger Sea waters.

However, we note in the time from *c.* 2.7 to 1.5 ka BP, a distinct rise in the planktic foraminifer concentration and thus an overall marked increase in the surface and subsurface water productivity (Fig. 3B). This is followed by an overall decrease in planktic foraminiferal concentration from *c.* 1.5 to 1 ka BP and only the values of *G. uvula* remain relatively high (Fig. 3B). We find that despite the marked decrease from *c.* 1.5 ka BP towards the present, the overall occurrence values (number of specimens g^{-1} sediment) of *T. quinqueloba* are higher than they are in the mid-Holocene period (*c.* 5.8 to 3 ka BP; Fig. 3B). The observed changes in the species foraminiferal concentration support the above assumption of cooler surface waters due to the SAF influence that is now located closer to the core site. The new $\delta^{18}O$ data for *G. bulloides* and *G. inflata* (Fig. 3C) illustrate a trend towards higher values during the last millennium, compared to the mid- to late Holocene average. Meanwhile, *N. incompta* data show the highest $\delta^{18}O$ values from *c.* 1.5 to 1.0 ka BP, indicating pronounced subsurface/mixed-layer cooling. However, a trend towards more depleted values, centred at *c.* 0.5 ka BP, suggests a brief warming of the mixed layer, which is in conflict with the continued higher values seen in *G. bulloides* and *G. inflata* (Fig. 3C).

Discussion

Regional mid- to late Holocene changes in surface and subsurface water-mass properties at the Reykjanes Ridge

Our new planktic foraminifer record reveals distinct shifts in the mid- to late Holocene surface and subsurface water-mass composition at the Reykjanes Ridge (Fig. 5). As previously outlined by Rasmussen *et al.* (2002) and Moros *et al.* (2012), here surface water changes result from variations in the location of the SAF. These studies suggest that mid- to late Holocene frontal migration occurs in response to variations in the inflow of warm/saline (IC/NAC) and fresh/cold (EGC advection that circulates around the Subpolar Gyre) waters at the

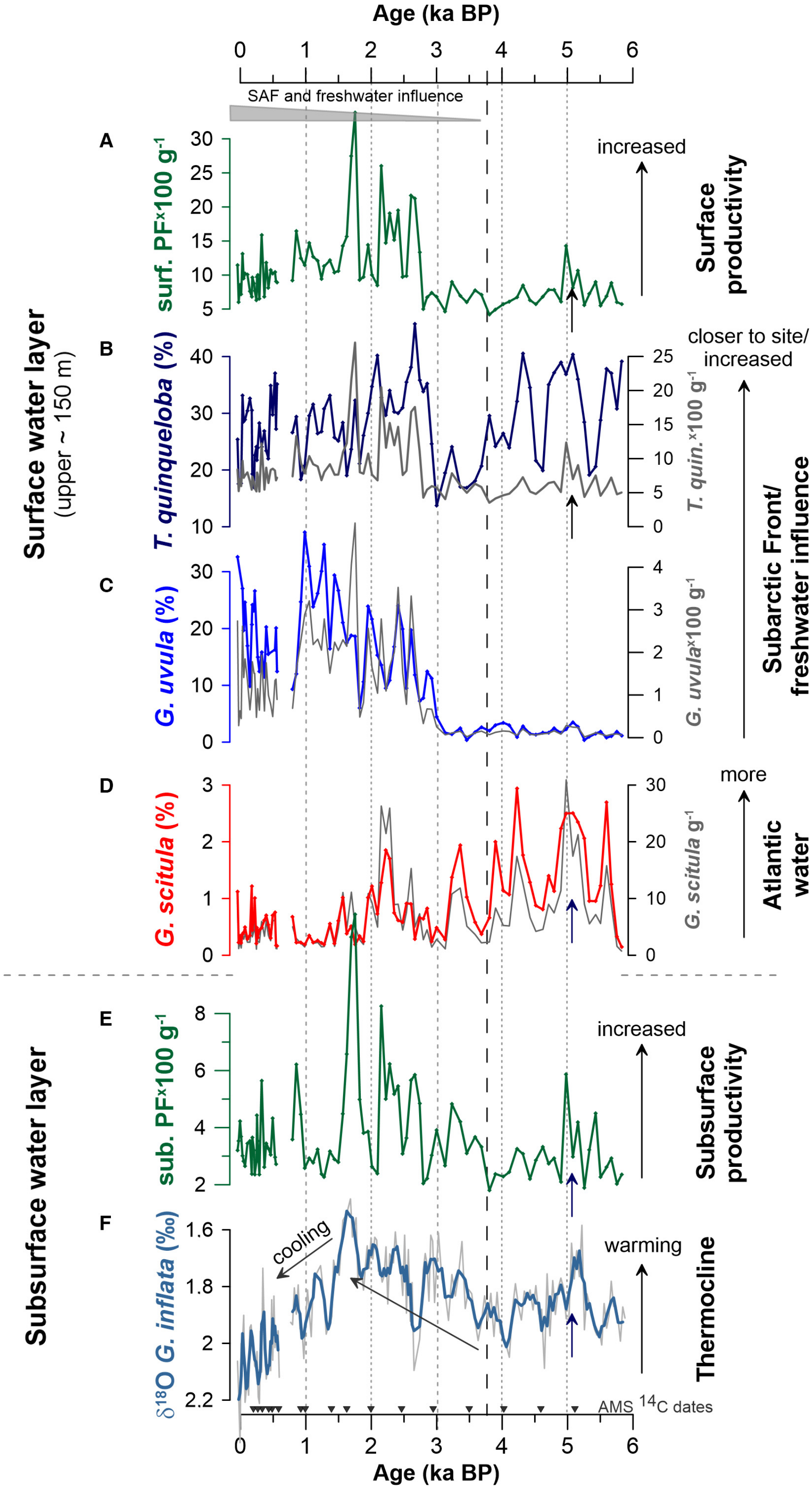


Fig. 4. Reconstructed mid- to late Holocene oceanic changes at the eastern Reykjanes Ridge. A. Surface water productivity group g^{-1}; B. Abundance (%; blue line) and concentration (g^{-1}; grey line) of *T. quinqueloba*. C. Abundance (%; light blue line) and concentration (g^{-1}; grey line) of *G. uvula*. D. Abundance (%; red line) and concentration (g^{-1}; grey line) of *G. scitula*. E. Subsurface water productivity group g^{-1}. F. Stable oxygen ($\delta^{18}O$) values of *G. inflata* (blue line). [Colour figure can be viewed at www.boreas.dk]

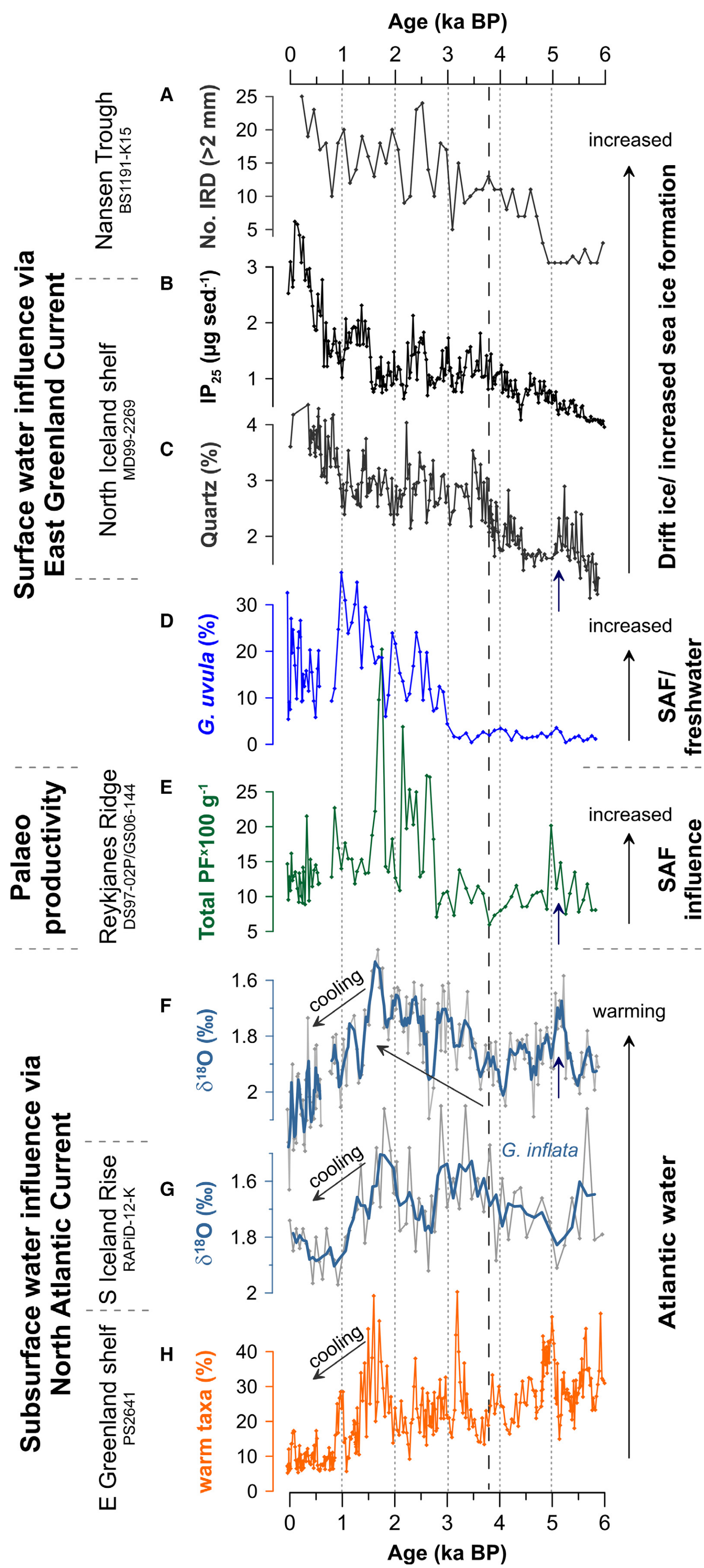
Ridge, which is in accordance with recent observations (e.g. Yoder *et al.* 1994; Bersch *et al.* 2007).

From *c.* 5.8 to 3.7 ka BP, overall relatively warm surface and subsurface water conditions prevail, with a well-developed mixed layer and deep thermocline (Figs 3, 4B, D, F). However, we note that two marked minima in the abundance of the oceanic front indicator *T. quinqueloba*, centred at *c.* 5.5 and 4.6 ka BP (Fig. 4B), parallel minima in the NAC indicator *G. scitula* (Fig. 4D). Both periods coincide with minor decreases in SST (Moros *et al.* 2004) and the occurrence of North Atlantic Drift (NAD) coccolith species (Solignac *et al.* 2009; Balestra *et al.* 2010). Furthermore, the calculated concentrations of surface and subsurface planktic foraminifera reveal increased productivity from *c.* 5.5 to 5.0 ka BP (Fig. 4A, D). This implies an enhanced influence of the SAF at our core site over a prolonged period. We speculate, based on the combined planktic foraminifer, coccolith and alkenone-derived SST evidence, that at *c.* 5.5 ka BP the SAF migrated southeastwards over the core site. Next, the front migrated northwest again, but probably remained well developed at the Reykjanes Ridge in the time at 5.0 ka BP, as a strong contrast between water-mass properties of the Iceland and Irminger Sea prevailed. Our reconstruction is in accordance with numerus studies from the NAC's main flow path that report a predominant warm/saline water influence on regional surface and subsurface water conditions during this time (e.g. Rasmussen *et al.* 2002; Risebrobakken *et al.* 2003, 2011; Solignac *et al.* 2004; Rasmussen & Thomsen 2010; Staines-Urías *et al.* 2013). The same accounts for the NAC's offshoots, such as the WSC (Müller *et al.* 2012; Werner *et al.* 2013; Rasmussen *et al.* 2014), the IC (e.g. Jennings *et al.* 2011; Andresen *et al.* 2013) and the WGC (e.g. Moros *et al.* 2006b, 2016; Erbs-Hansen *et al.* 2013; Perner *et al.* 2013; Jennings *et al.* 2014; Sha *et al.* 2014). Even records from the Greenland Sea (Telesiński *et al.* 2014) and from the central East Greenland shelf (Fig. 5H; Perner *et al.* 2015) report the presence of warm subsurface waters. Simultaneously, studies from the North Iceland shelf (EGC-influenced; e.g. Moros *et al.* 2006a), north of Newfoundland (LC-influenced; e.g. Solignac *et al.* 2011) and from the southeast sub-polar North Atlantic (e.g. Bond *et al.* 2001) report the occurrence of cool and fresh, ice-bearing surface waters. Henceforth, we infer that the mid-Holocene strengthening (well developed) and migration of the SAF at the Reykjanes Ridge (*c.* 5.5 to 5.0 ka BP) resulted from a steeper gradient between water-masses in the Iceland and Irminger Sea. However, this gradient weakened afterwards, as seen in decreasing surface and subsurface productivity (Fig. 4B, E). We postulate that in the time from *c.* 4.5 to 3.7 ka BP, the SAF either migrated further to the northwest of our core site and/or weakened, i.e. was less well developed at the Reykjanes Ridge.

From *c.* 3.7 to 3.0 ka BP, the abundance of the oceanic front indicator *T. quinqueloba* decreases markedly (Fig. 4B). This accompanies a peak in abundance of the NAC indicator *G. scitula* (Fig. 4D) and gradual subsurface warming (Fig. 4F) compared to the preceding interval. Simultaneously, a 1 °C SST rise (Moros *et al.* 2004) and an increased abundance of NAD coccolith species (Solignac *et al.* 2009; Balestra *et al.* 2010) indicate enhanced surface water productivity. These assumptions support our planktic foraminiferal concentration data (Fig. 4A, E). However, our data also indicate an overall weaker SAF influence on our core site compared to the *c.* 5.5 to 5.0 ka BP period. Presumably, the SAF prevailed northwest and/or simply was less sharply developed at the Ridge. Concomitantly, recent studies infer increased ice-loaded surface waters on the East Greenland and North Iceland shelf, i.e. strong EGC, from *c.* 4.5 ka BP onwards (Fig. 5A–C; Andrews *et al.* 1997, 2010; Moros *et al.* 2006a; Perner *et al.* 2015, 2016; Cabedo-Sanz *et al.* 2016). Simultaneously, subsurface temperature records from the region document a gradual and/or stepwise warming from *c.* 3.7 to 3.0 ka BP (Fig. 5F, G; Hall *et al.* 2004; Thornalley *et al.* 2009; Farmer *et al.* 2011; Moros *et al.* 2012). Related to this subsurface warming, several studies from the SE and W Greenland shelf report relatively warm surface and subsurface water conditions alongside increased phytoplankton productivity (Moros *et al.* 2006b, 2016; Jennings *et al.* 2011; Andresen *et al.* 2013; Perner *et al.* 2013, 2016; Sha *et al.* 2014).

From *c.* 3.0 ka BP onwards, the sudden increase of *G. uvula* reflects a distinct shift in the surface water composition at the eastern Reykjanes Ridge (Fig. 4D). We postulate that the sudden appearance of this opportunistic species (Bé 1977) indicates an overall enhanced influence of colder and fresher surface water. This agrees well with the reported increase in drift and sea ice and freshwater advection through Fram Strait and a southward shift of the Polar Front in the subpolar North Atlantic (e.g. Moros *et al.* 2006a; Jennings

Fig. 5. Comparison of palaeoceanographic conditions at the Reykjanes Ridge with drift/sea-ice records from the East Greenland and North Iceland shelfs. A. IRD counts from outer Nansen Trough (BS1191-K15) from Andrews *et al.* (1997). North Iceland shelf proxy data (site MD99-2269): B. Concentration of sea-ice marker IP25 (μg sed.$^{-1}$) from Cabedo-Sanz *et al.* (2016) and C. Quartz content (%) as drift ice indicator from Moros *et al.* (2006a). Proxy data from this study: D. Abundance (%) of *G. uvula*. E. Total planktic foraminifer productivity (g^{-1}). F. δ^{18}O data of thermocline dweller *G. inflata* (blue line three-point average; DS97-02P from Moros *et al.* 2012). G. δ^{18}O data of thermocline dweller *G. inflata* from the South Iceland Rise, core RAPiD-12-k (blue line three-point average; Thornalley *et al.* 2009). H. Relative abundance data (%) of benthic foraminifer Atlantic Water indicator species, documenting subsurface water conditions on the central East Greenland shelf at 73°N (Perner *et al.* 2015). [Colour figure can be viewed at www.boreas.dk]


Age (ka BP)
0 1 2 3 4 5 6
A
B
C
D
E
F
G
H
Surface water influence via East Greenland Current
Nansen Trough
BS1191-K15
North Iceland shelf
MD99-2269
No. IRD (>2 mm)
IP25 (µg sed-1)
Quartz (%)
G. uvula (%)
increased
Drift ice/ increased sea ice formation
SAF/ freshwater
Palaeo productivity
Reykjanes Ridge
DS97-02P/GS06-144
Total PF×100 g-1
SAF influence
Subsurface water influence via North Atlantic Current
S Iceland Rise
RAPiD-12-K
E Greenland shelf
PS2641
δ18O (‰)
warm taxa (%)
cooling
warming
G. inflata
Atlantic water

et al. 2011; Müller *et al.* 2012; Werner *et al.* 2013; Perner *et al.* 2015; Cabedo-Sanz *et al.* 2016). Concomitantly, subsurface warming occurs at the Reykjanes Ridge (Fig. 5F) and in the Iceland Sea (Fig. 5G; Hall *et al.* 2004; Thornalley *et al.* 2009). Moros *et al.* (2012) linked this warming to the time of the Roman Warm Period (RWP). We argue that the pronounced rise in surface and subsurface water productivity (Fig. 4A, E) results from a strengthening of the SAF and frontal migration over our core site. Periods of increased productivity occur from *c.* 2.7 to 2.2 ka BP and at *c.* 1.8 ka BP. This is in line with Rasmussen *et al.* (2002), who identified several diatom mats at our core site that they linked to strong changes in surface water productivity caused by repeated migrations of the SAF. Alkenone, coccolith and diatom (-mats) records from nearby core LO09-14 record a variable influence of NAC- and EGC-fed water-masses on surface water conditions (Andersen *et al.* 2004b; Witak *et al.* 2005; Solignac *et al.* 2009; Balestra *et al.* 2010).

From *c.* 1.5 ka BP towards the present, the prominent decrease in surface and subsurface water productivity suggests that the SAF weakened and/or shifted further southeastwards at the Reykjanes Ridge. We postulate that surface water advection of the EGC, which circulates around the Subpolar Gyre, predominantly influenced our core site, particularly in the time from *c.* 1.5 to 1.0 ka BP. Here, *G. uvula* dominates the fauna (abundance and flux wise; Fig. 5D), although surface water productivity and temperatures markedly decreased within the area (Fig. 4A; e.g. Hall *et al.* 2004; Moros *et al.* 2004, 2012). We argue that due to its opportunistic character *G. uvula* was able to thrive/compete in the now colder/fresher, EGC-influenced, surface waters. Our findings of a more southeastward located SAF agree well with reports of SST cooling and a markedly reduced abundance of NAD cocccoliths from site LO-09-14 (Andersen *et al.* 2004b; Solignac *et al.* 2009; Balestra *et al.* 2010). This is associated with subsurface (thermocline) cooling as illustrated by markedly enriched $\delta^{18}O$ values of *G. inflata* (Fig. 5F, G; Hall *et al.* 2004; Thornalley *et al.* 2009; Moros *et al.* 2012). Findings of a reduced contribution of warm and saline waters from the NAC to our core site may either result from a weaker IC, which shifted southwards, and/or a slowdown of ocean currents (e.g. Rasmussen *et al.* 2002; Hall *et al.* 2004).

During the last millennium, surface and subsurface water productivity remains on a higher level (Fig. 4A, E), which implicates a continuously strong SAF influence when compared to the mid-Holocene conditions (*c.* 5.8 to 3.0 ka BP). We infer from the relatively high abundance of *G. uvula* and *T. quinqueloba* (Fig. 4B, C) that the SAF probably lingered close to, but probably more to the southeast of our core site on the Ridge. This accompanies a further gradual cooling of thermocline waters (Fig. 4F), which agrees well with previous reports of a well-mixed upper water column in the wider area (e.g. Hall *et al.* 2004).

Regional oceanic implications

Our planktic foraminifer data document a prominent mid- to late Holocene shift of oceanic conditions at the Reykjanes Ridge (Fig. 5D). The inferred mid- and late Holocene frontal migration and/or strengthening phases, from *c.* 5.5 to 5.0 and *c.* 2.7 to 1.5 ka BP, differ markedly from each other. Thereby, the relative contribution of cold and fresh waters into the sub-polar North Atlantic plays a crucial role.

The first period of a marked SAF developed at the Reykjanes Ridge (*c.* 5.5 to 5.0 ka BP) encompasses distinct changes in the southward export of Arctic Ocean waters via the EGC and, presumably, within the LC, which circulate around the Subpolar Gyre. Palaeoceanographic studies from the Arctic Ocean report increased sea-ice formation after *c.* 6.0 ka BP (Bauch *et al.* 2001; Stein *et al.* 2017). This agrees well with findings from the Fram Strait and Barents Sea (sensitive to Polar Front migration) and the East Greenland and North Iceland shelf that document cooler and more ice-loaded surface waters around the same time (e.g. Andrews *et al.* 1997, 2010; Moros *et al.* 2006a; Müller *et al.* 2012; Werner *et al.* 2013). Concomitantly, studies from the western sub-polar North Atlantic report enhanced contribution of cooler and fresher waters to the LC (e.g. Scott & Collins 1996; Solignac *et al.* 2011). This favoured surface cooling and sea-ice growth in the Labrador Sea (e.g. Reverdin *et al.* 1997; Deser *et al.* 2002). Therefore, the development of a marked SAF and/or frontal migration in the mid-Holocene seems to be a response to an increase in the freshwater expansion within the sub-polar North Atlantic.

However, Moros *et al.* (2012) noted that until *c.* 3.7 ka BP the IC subsurface (thermocline) temperature on the eastern Reykjanes Ridge ran parallel to those recorded within the main flow path of the NAC (e.g. Risebrobakken *et al.* 2003). The authors linked the following divergence between these two Atlantic Water branches, i.e. NAC and IC, to a widespread freshening of the surface water layer in the sub-polar North Atlantic. This supports reports of decreased abundance of the near-surface dweller *G. bulloides* (Fig. 3; Rasmussen & Thomsen 2010; Staines-Urías *et al.* 2013) as well as reduced SSTs along the NAC/NwAC (e.g. Calvo *et al.* 2002; Marchal *et al.* 2002; Andersen *et al.* 2004a, b). The observed warming of subsurface (thermocline) waters within the IC between *c.* 3.7 and 1.5 ka BP (Hall *et al.* 2004; Thornalley *et al.* 2010; Moros *et al.* 2012) and along the NAC's flow path, particularly around the time of the RWP (e.g. Andrews & Giraudeau 2003; Risebrobakken *et al.* 2003; Sarnthein *et al.* 2003; Andersen *et al.* 2004a; Giraudeau *et al.* 2010; Perner *et al.* 2011, 2016; Sejrup *et al.* 2011; Werner *et al.* 2013) may, therefore, result from various causes. Subsurface warming may simply be a response to the increased stratification of the upper ocean layer, and hence, a less ventilated subsurface that caused heat accumulation (e.g. Bauch *et al.* 2001; Hall *et al.* 2004; Hald *et al.* 2007). It may also be a response to enhanced contribution of subtropical waters to the NAC (Morley *et al.* 2014; Repschläger *et al.* 2015) triggered by the '*c.* 2.7 ka BP cooling event' that probably caused an AMOC slowdown (e.g. Oppo *et al.* 2003) and thus created thereafter a heat overshoot.

The prominent post-RWP weakening of the SAF (Fig. 5E) and cooling of subsurface (thermocline; Fig. 5F, G) waters parallel reports of markedly less warmth (heat) along the NAC's main route (e.g. Risebrobakken *et al.* 2003; Andersen *et al.* 2004a; Rasmussen & Thomsen 2010; Sejrup *et al.* 2011; Dylmer *et al.* 2013; Staines-Urías *et al.* 2013; Dourarin *et al.* 2016). Upstream, studies from the eastern Fram Strait (Müller *et al.* 2012; Werner *et al.* 2013; Rasmussen *et al.* 2014) and from the central East Greenland shelf (Fig. 5H; Perner *et al.* 2015) document a marked reduction in NAC-sourced waters. Similar evidence is found along the SE and W Greenland shelf areas (e.g. Kuijpers *et al.* 2003; Andersen *et al.* 2004a; Moros *et al.* 2006b, 2016; Lloyd *et al.* 2007; Jennings *et al.* 2011; Perner *et al.* 2011, 2016; Andresen *et al.* 2013; Gibb *et al.* 2015). This implies a widespread freshening and cooling of subsurface waters within the sub-polar North Atlantic region. However, it remains to be seen if this cooling and freshening is simply a result of more relaxed (reduced) ocean current flow and/or reduced contribution of warmth from the subtropics to the NAC.

Conclusions

The combined planktic foraminifer and $\delta^{18}O$ data from the eastern Reykjanes Ridge provide detailed insights into the expansion of mid- to late Holocene fresh and sea-ice loaded surface waters within the sub-polar North Atlantic. Advection of these waters around the Subpolar Gyre, originating in the EGC, affects the location of the SAF at the Reykjanes Ridge. A prominent mid- to late Holocene shift in oceanic conditions occurs at *c.* 3.0 ka BP, reflecting an enhanced freshwater expansion and SAF influence at our core site. We identify two phases of SAF migration and strengthening, from *c.* 5.5 to 5.0 and 2.7 to 1.5 ka BP. These phases characterize a prominent increase in productivity of the surface and subsurface waters (upper ocean layer – ~200 m water depth). From *c.* 5.5 to 5.0 ka BP, initial frontal strengthening occurs in response to enhanced contribution of fresh and ice-loaded surface waters from the Arctic Ocean along the EGC route. From *c.* 3.7 ka BP, the freshwater and SAF influence increases. We infer the late Holocene maximum SE location of the front from *c.* 2.7 to 1.5 ka BP. A well-developed SAF most likely resulted from the interaction of opposing water-masses at the Reykjanes Ridge, i.e. the simultaneous influence of the warm and saline NAC and cold and fresh EGC. Several palaeoproxy studies noted enhanced freshwater and sea-ice advection along the EGC route, suggesting expansion of a surface freshwater layer within the sub-polar North Atlantic. Therefore, the subsurface warming at the Ridge reflects either enhanced heat accumulation, i.e. reduced ventilation, in response to a thick freshwater layer and/or enhanced advection of subtropical waters into the NAC. However, our data show, in agreement with previous studies, that from *c.* 1.5 ka BP onwards, surface waters remain relatively cool and fresh at the Ridge. This parallels a prominent subsurface (thermocline) cooling at the Reykjanes Ridge and elsewhere in the sub-polar North Atlantic along the NAC and its offshoots. Accordingly, we infer a continuous frontal influence that implicates a more southeast located SAF relative to our core site. Assessing the spatial freshwater extent and location of the SAF during the late Holocene more accurately requires further similar studies on sites further south of our core location.

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